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H. S. Chin, P. M Caldwell, D. C. Bader

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Hung-Neng S Chin, Peter M. Caldwell, and David C. Bader

Atmospheric, Earth, and Energy Division
Lawrence Livermore National Laboratory
Livermore, California

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Corresponding author address: Dr. Chin, Lawrence Livermore National Laboratory, P. O. Box 808 (L-103), Livermore, CA 94551, Email: chin2@llnl.gov.

Abstract

The Weather and Research Forecast (WRF) model version 3.0.1 is used to explore California wintertime model wet bias. In this study, two wintertime storms are selected from each of four major types of large-scale conditions; Pineapple Express, El Nino, La Nina, and synoptic cyclones. We test the impacts of several model configurations on precipitation bias through comparison with three sets of gridded surface observations; one from the National Oceanographic and Atmospheric Administration, and two variations from the University of Washington (without and with long-term trend adjustment; UW1 and UW2, respectively). To simplify validation, California is divided into 4 regions (Coast, Central Valley, Mountains, and Southern California). Simulations are driven by North American Regional Reanalysis data to minimize large-scale forcing error. Control simulations are conducted with 12-km grid spacing (low resolution) but additional experiments are performed at 2-km (high) resolution to evaluate the robustness of microphysics and cumulus parameterizations to resolution changes.

We find that the choice of validation dataset has a significant impact on the model wet bias, and the forecast skill of model precipitation depends strongly on geographic location and storm type. Simulations with right physics options agree better with UW1 observations. In 12-km resolution simulations, the Lin microphysics and the Kain-Fritsch cumulus scheme have better forecast skill in the coastal region while Goddard, Thompson, and Morrison microphysics, and the Grell-Devenyi cumulus scheme perform better in the rest of California. The effect of planetary boundary layer, soil-layer, and radiation physics on model precipitation is weaker than that of microphysics and cumulus processes for short- to medium-range low-resolution simulations. Comparison of 2-km and 12-km resolution runs suggests a need for improvement of cumulus schemes, and supports the use of microphysics schemes in coarser-grid applications.

1. Introduction

As a result of coarse grid resolution and inadequate model physics, global climate models (GCMs) are currently unable to produce reliable climate information on the scale needed to assess regional climate-change impacts and variability. To assess the possible societal impacts of climate changes, many regional climate models (RCMs) have been developed and used to provide projections of future regional-scale climates for guiding policies in economy, ecosystem, water supply, agriculture, human health, and air quality (Giorgi et al., 1994; Leung and Ghan, 1999; Leung et al., 2003; Liang et al., 2004b; Kim, 2004; Duffy et al., 2006; Caldwell et al., 2009). Although many regional climate features have been successfully captured in RCMs, obvious biases in simulated precipitation remain, particularly the wintertime wet bias commonly seen in mountain regions of the Western United States. Precipitation bias in coastal ranges has historically also been large mainly due to inadequate grid resolution in earlier RCM studies.

The strong scale interaction between atmospheric circulation, ocean and topography in the Western United States provides a challenging testbed for RCMs. Within this region, California is especially important not just because it has the largest population in the nation, but because it has one of the most sophisticated water collection and distribution systems in the world. Adapting California's water management systems to climate change presents significant challenges. Therefore, a credible regional modeling capability is essential for understanding and preparing for the impacts of climate change on the temporal and spatial scales that are critical to California.

Currently, the most popular method for obtaining regional climate prediction is to run a numerical weather prediction model forced at the lateral boundaries and sea surface with predictions from a GCM. Forecast bias in such coupled modeling systems can arise from the quality of the GCM forcing, from imperfect lateral boundary conditions in RCMs, and from problems with the RCM physics and numerics. Additionally, errors in the datasets used for validation can strongly affect the apparent size of model bias. Therefore, it is difficult to detect the primary sources of such bias in this type of framework. To this end, the WRF model along with multiple sources of surface measurements are used to examine the impact of model physics and validation uncertainty on the precipitation bias in this study.

This study has three objectives. The first is to gauge the sensitivity of model precipitation to standard parameterization options for each physical process. The second is to examine how observational dataset choice impacts our conclusions about model bias. The final objective is to compare WRF simulations at 2-km and 12-km resolutions in order to test the robustness of microphysics and cumulus parameterizations to resolution changes. The model setup, experiment design, and measurements used to validate the model are presented in Section 2. Section 3 shows the results for the assessment of model physics sensitivity, validation uncertainty, and grid resolution impact. A summary and discussion follow in section 4.

2. MODEL DESCRIPTION, EXPERIMENT DESIGN, AND MEASUREMENTS

a. Model Setup and Initialization

The model used in this study is the Advanced Research WRF (ARW) modeling system version 3.0.1, a community model maintained by the National Center for Atmospheric Research. The ARW is non-hydrostatic and fully compressible. It uses the sigma-pressure coordinate in the vertical to better simulate air flow over complex terrain. The model has a flux-form set of governing equations for better numerical conservation of mass and scalars. The model physics contains cumulus convection, microphysics of cloud processes and precipitation, long- and shortwave (LW and SW) radiation, turbulence and diffusion, a planetary boundary layer (PBL) scheme, a surface layer parameterization, and soil layer representations. There are a variety of choices for each of the physical processes. The reader is referred to Skamarock et al. (2008) for further details.

Nested grids are used in a limited horizontal domain size to minimize the impact of outer lateral boundary conditions (LBCs) on the model solution. Seth and Giorgi (1998) found that small RCM domains produce spurious LBC dynamic effects and cause the RCM to generate unrealistic responses to internal forcing. Ten grid points are specified in each relaxation zone of the outer boundaries with the exponential multiplier set to 0.2 in this study.

The vertical axis contains 31 levels with 20 m resolution near the ground and gradually coarser spacing aloft. The domain top resides at the height of 100 mb. Static fields (e.g., land-use, terrain, and soil-type) with a resolution of 30 arc second are used to initialize simulations. Positive definite advection is turned on for moisture variables, and sea surface temperature is updated throughout simulations. The third-order Runge-Kutta scheme is adopted in the time-splitting integration with sound waves treated explicitly in the horizontally and implicitly in the vertical on shorter sub-steps. 5^{th} and 3^{rd} order schemes are used for the horizontal and vertical advection, respectively.

Eight events are chosen as representatives of California wintertime precipitating storms from four major types of large-scale conditions; two of each type. These storms include Pineapple Express, El Nino, La Nina, and synoptic cyclone (see Table 1). More description of these selected storms can be seen in Dettinger (2004) and Null (2004). Six of these events caused flood and severe local damage in different portions of California. Brief description of these large-scale circulations and their hydrological consequences in California can been seen in Dettinger et al. (2004). All simulations last for 3 to 11 days. The initial and lateral boundary conditions of this study are based on North American Regional Reanalysis (NARR) data at a spatial resolution of

32 km, and the temporal interval of six hours. Reanalysis data provide our most realistic large-scale forcings, which allow us to focus on the model bias caused by WRF.

b. Experiment Design

Table 2 lists the model physics options used in this study. The choice of these options for each physical process is based on consideration of consistent interaction among processes and forecast skill. Due to its direct influence on cloud and precipitation processes, the impact of microphysics on model precipitation is addressed in more detail. Five microphysics schemes are tested in 12-km simulations; Lin (Lin et al., 1983), WSM 5 class (WSM5; Hong et al., 2004), Goddard 3ice scheme with graupel (Tao et al., 2003), Thompson (Thompson et al., 2008), and Morrison (Morrison et al., 2005). All microphysics options are single-moment schemes except Morrison (a two-moment scheme). Other physics modules include cumulus parameterization from Kain-Fritsch (Kain, 2004), and Grell-Devenyi (Grell and Devenyi, 2002), soil-layer modules from Noah (Chen and Dudhia, 2001), and RUC (Smirnova et al., 2000), planetary boundary layer (PBL) physics from YSU (Hong et al., 2006), and ACM2 (Pleim, 2007), and radiation from RRTM LW / Dudhia SW (Mlawer et al., 1997 / Dudhia, 1989), and CAM LW/SW (Collins et al., 2004). The Noah soil-layer scheme used in this study has additional snow albedo and deep soil temperature updates, as in ARW version 3.1. The control configuration of physics options is set to Morrison microphysics, Grell-Devenyi cumulus, Noah land soil module, YSU PBL, and CAM radiation transfer.

In this study, we perform two sets of nested-grid simulations with two-way coupling. The first set (referred as low resolution) has two levels of nested grids with resolutions of 36 and 12 km, respectively, and is primarily used to study the sensitivity of forecast precipitation to all model physics and storm types. The other simulations (high resolution) are conducted using three levels of nested grids at 18, 6, and 2 km, respectively. Comparison of low- and high-resolution simulations is used to assess the robustness of microphysics and cumulus parameterizations in coarser-grid applications. Due to the computational cost, we only perform high-resolution simulations for four storm events (one of each large-scale condition; PE2, EN1, LN1, and SC1) and three microphysics schemes (Lin, Goddard and Morrison). Only the results from the inner-most domain (100 x 130 and 544 x 712 grids in x and y axis, respectively) of low- and high-resolution simulations are shown in this study. Time steps for the model domains of 2-km and 12-km resolutions are 6.67 and 40 seconds, respectively.

Figure 1 exhibits model terrain and inner domain coverage of both 12-km and 2-km simulations. The topography in the high-resolution run clearly shows finer structure and larger magnitude in mountain areas and coastal ranges. Within these simulated domains, California is divided into 4 regions; Coast, Central Valley (C_Valley), Mountain (Mtn), and Southern California (S_Cal). Averages over these regions are used for validation.

c. Measurements for Validation

In this study, we use three gridded observational precipitation datasets to assess the sensitivity of model precipitation bias to observation sources. The first is from the National Oceanic and Atmospheric Administration with a spatial resolution of 0.25° (referred to as NOAA); this dataset has no terrain correction. The other two are from the University of Washington (UW) with a grid resolution of 0.125°. The NOAA data set uses more rain-gauge stations than UW, but UW's data have topography adjustment to match that of the Parameter-elevation Regressions on Independent Slopes Model (PRISM) dataset (Maurer et al., 2002; UW1). In addition to terrain correction, one of the UW datasets includes additional adjustment for temporal heterogeneities, which makes it more appropriate for the long-term trend analysis

(Hamlet and Lettenmeier, 2005; UW2). Note that for the LN2 case, only UW2 measurements are available for validation.

3. RESULTS

a. Sensitivity of Model Precipitation to WRF Physics

Precipitation is the most important variable for climate studies, so low precipitation bias is an important measure of success in regional climate simulations. Given the driving large-scale conditions, the success of RCM forecasts depend strongly on the accuracy of model physics representations and the interactions between physical processes. This section describes a series of experiments at 12-km resolution to examine the sensitivity of simulated precipitation to individual model physics.

a.1 Microphysics Schemes

Figure 2 illustrates the distribution of convective (parameterized) and stratiform (resolved) surface precipitation simulated with five different microphysics schemes from a California wintertime synoptic cyclone case (SC1). All simulations show that stratiform precipitation primarily appears in the high-elevation mountain region while convective rain is mainly located in the coastal region. The overall patterns of convective and stratiform precipitation are barely influenced by microphysics schemes (either single- or two-moment). The primary impact of microphysics schemes on simulated precipitation is seen in the magnitude. Magnitude changes are also the major impacts of varying microphysics schemes for the other storms studied (not shown). The narrow band of simulated stratiform precipitation found in the Morrison scheme for California wintertime storms is at odds with the results of Morrison et al. (2009) for summertime severe storms; they found the two-moment scheme to cause wider spreading of surface precipitation as a result of weaker evaporation of rainwater below the melting layer. This difference may arise from weaker convective instability of California wintertime storms, which results in less horizontal transport of ice-phase hydrometeors from the detrainment layer of deep convective towers.

The impact of microphysics schemes on simulated surface total precipitation in individual regions of California for all selected storms is described in Fig. 3, which compares spatially- and temporally-averaged precipitation between simulations and observations. In addition to the sensitivity of model results to microphysics schemes, observations from different sources of gridded measurements differ markedly. This discrepancy leads to high sensitivity of simulated precipitation bias to validation datasets. As an example, the mean absolute error (MAE) of model precipitation using the Morrison scheme in the mountain region over all storms except LN2 (Fig. 3b) is 13.1% as validated with UW1 dataset, but 32.4% and 38.3% for UW2 and NOAA data, respectively. The difference between UW2 and UW1 datasets is due to the inclusion of long-term trend adjustment, which clearly weakens precipitation over California for all storms. In low-elevation regions, such as Southern California and Central Valley, UW1 and NOAA datasets agree better. In coastal and mountain regions, topographical adjustment (not included in NOAA dataset) becomes important resulting in larger differences between UW1 and NOAA datasets.

As a whole, model forecast skill in surface precipitation depends strongly on geographic location and storm type. All schemes exhibit considerable overestimation of surface precipitation for the La Nina type of storms over all regions of California except the coast. For the rest of the storm types, Microphysics schemes show better agreement with observations (in particular with UW1) in mountain and Southern California regions. Noticeable underestimation appears in the coastal region and overestimation occurs in the Central Valley region. In addition, the Lin microphysics scheme seems to predict stronger precipitation than the other microphysics options in most of storm types and regions. As a result, the Lin scheme gives a smaller MAE of model precipitation in the coastal region (11.3%, 11.4%, and 12.6% with respect to UW1, UW2, and NOAA, respectively), but does worse in the other regions where precipitation is generally overpredicted (e.g., MAE of 21.29%, 47.99%, and 63.56% in the mountain region with respect to UW1, UW2, and NOAA, respectively). Based on comparison of model simulations with different observational datasets, our results indicate that UW1 observations give the smallest precipitation bias.

Table 3 summaries the forecast precipitation bias (with respect to UW1 datasets) averaged with equal weight over all selected storms except LN2. Results indicate that the Lin scheme exhibits the best forecast skill in the coast but the Morrison (two-moment) scheme shows the best performance in the mountain region. In contrast, all microphysics schemes poorly predict precipitation in the Central Valley while all of them have reasonable skill in Southern California. If we consider observed frequencies of all large-scale conditions in California, the model forecast precipitation bias in longer time-scale average may be better than those shown in Table 3 since synoptic-scale cyclones are the predominant type of large-scale conditions, and the model exhibits better forecast skill for this type of storms, particularly in the mountain region.

a.2 Cumulus Parameterizations

The Kain-Fritsch (KF) and Grell-Devenyi (GD) schemes are chosen for this study because they outperformed other cumulus parameterizations in earlier modeling studies (e.g., Kerkhoven et al., 2005). The major difference of these two parameterizations is the treatment of entrainment / detrainment mixing of convection; The KF scheme assumes this mixing occurring throughout the whole depth of convection while the GD scheme only allows this to occur at the cloud top. Liang et al. (2004a) demonstrated that the GD scheme is very responsive to large-scale forcing whereas the KF scheme is heavily influenced by boundary-layer forcing. Another study indicated that the partition between parameterized and resolved precipitation is very sensitive to the cumulus scheme (Liang et al., 2004b), a feature also found in this study (not shown).

Figure 4 illustrates the impact of cumulus parameterizations on simulated total (convective and stratiform) precipitation. As compared to the GD scheme, the KF scheme acts to enhance surface total precipitation over all regions for all microphysics schemes. The precipitation enhancement by the KF scheme with respect to the GD scheme was also reported by Liang et al. (2004b) for a summertime East Coast case. One exception occurs in the Central Valley for the LN2 case, where KF precipitation is weaker for all microphysics schemes. Since coastal precipitation is generally underpredicted and precipitation in other regions is generally overpredicted, the KF scheme improves coastal precipitation forecasts, but the GD scheme remains a better choice in the other portions of California. As found in previous studies, cumulus parameterization has a significant impact on precipitation prediction. It is, however, beyond the scope of this study to determine what aspects of the parameterizations cause the differences in precipitation prediction, but we speculate that differences in cumulus entrainment / detrainment treatment play a leading role.

a.3 Other Physics

Planetary boundary layer, soil layer, and radiation transfer play indirect roles in cloud / precipitation processes by changing the atmosphere’s thermodynamic structure. Interactions between surface and the atmosphere have been the focus of modeling studies on a wide range of time and spatial scales (e.g., Pielke, 2001; Koster et al., 2004). Soil moisture and temperature have an important effect on the determination of surface sensible and latent heating fluxes, and could therefore have a profound influence on the development of clouds, the PBL and surface energy budgets particularly for longer time scales (Small and Kurc, 2001).

The impact of model physics other than cloud processes on simulated surface precipitation is depicted in Fig. 5. Our results indicate that this impact is weaker than that of microphysics and cumulus parameterizations for all studied storms. Part of this low sensitivity is due to slow influence of these physics processes in short- to medium-range simulations. Therefore, these processes are unlikely the major cause of precipitation forecast bias in this study, but could be an issue in longer simulations.

As compared to UW1 observations, the ACM2 PBL scheme performs like the control setting (YSU) at 37.5% of cases (combination of storm types and regions), and works better / worse than YSU at 18.8% / 43.7%, respectively. Similarly, the RUC soil-layer and the RRTM LW / Dudhia SW radiation schemes have a chance of 25% / 31.3% and 21.9% / 40.6%, respectively to perform better / worse than the control setting. Therefore, the use of PBL, soil layer, and radiation transfer options other than the control setting tends to slightly increase precipitation forecast bias.

b. Impact of Grid Resolutions on Model Precipitation

Most microphysics schemes were originally designed for use in cloud-resolving models with higher horizontal grid resolutions (~ 1 km or less). However, these microphysics schemes have been widely used in RCMs for regional climate research. Therefore, it is of importance to assess the performance of microphysics schemes for coarser-grid applications. Comparison of the spatial distribution from both high- (2-km) and low-resolution (12-km) simulations with the control configuration of the physics options for four selected storms from different large-scale conditions indicates that the simulated precipitation pattern exhibits strong similarity between both sets of simulations (Fig. 6). The only noticeable difference is stronger precipitation in higher-resolution runs. Similar results also appear in simulations with different microphysics schemes (not shown). Note that the cumulus parameterization is turned off in the high-resolution experiments.

Comparison of area-averaged statistics for high- and low-resolution simulations against UW1 observations indicates that higher grid-resolution greatly improves surface precipitation in the coastal region, particularly with the Morrison (two-moment) scheme (Fig. 7a). However, these high-resolution simulations lead to substantial overestimation of surface precipitation in mountain and Central Valley regions (Fig. 7b). This result suggests that 12-km resolution is not enough to represent the orographic forcing at the coastal ranges, although it has shown great improvement in surface precipitation forecast as compared to earlier RCMs (Leung et al., 2003; Kim, 2004; Duffy et al., 2006). The cause of the degraded performance of high-resolution simulations in the high-elevation mountain region remains unclear. More effort is needed to clarify whether this issue is caused by a numerical problem in the handing of steep terrain by the sigma-pressure coordinate model, or by insufficiency of the microphysics schemes for handling the geographic location of our study. This grid-resolution impact also indicates the need to improve the performance of cumulus schemes in coarser-grid applications. In addition, the validation of low- and high-resolution simulations with measurements supports the argument for using microphysics schemes in coarser-grid applications. These findings have valuable implications on regional climate simulations due to the need of large computational power.

4. SUMMARY AND DISCUSSION

The complete model physics and multiple options of each physics module in WRF enable us to thoroughly study process interactions, and help determine an optimal physics configuration for better model performance. The ARW modeling system version 3.0.1 was used in this study to explore California wintertime model wet bias. This work was motivated by the existence of large wet bias in the western United States in many earlier RCM studies. Major effort was placed on assessing the impacts of WRF physics options and measurements uncertainty.

We chose eight California wintertime storms from four major types of large-scale conditions, including Pineapple Express, El Nino, La Nina, and synoptic cyclones in this study. The duration of simulated storm events ranged from 3 to 11 days. North American Regional Reanalysis data provide inputs for simulations with two-way coupling nested grids. We tested the skill of physics configurations (e.g., microphysics, cumulus parameterization, planetary boundary layer, soil layer, and radiation transfer) against 3 sets of gridded observations (NOAA, UW1, and UW2). California is divided into 4 regions for validation; Coast, Central Valley, Mountain, and Southern California. Control simulations were conducted with 12-km grid spacing to study the sensitivity of forecast precipitation to all model physics and storm type. Additional experiments were performed at 2-km resolution to evaluate the robustness of microphysics and cumulus parameterizations in coarser-grid applications.

We find that the choice of validation datasets has a significant impact on the magnitude of model precipitation bias, particularly in the mountain region. For the simulations with optimal physics configuration, our results indicate that averaged over all storm types, UW1 observations give the smallest forecast bias than UW2 and NOAA datasets. The largest difference appears in the mountain region (MAE of 13.1% in UW1, 32.4% in UW2 and 38.3% in NOAA). Our results suggest that the forecast skill of model precipitation depends strongly on geographic location and storm type. In low-resolution (12-km) simulations, the Lin microphysics and the Kain-Fritsch cumulus scheme have better forecast skill in the coastal region while Goddard, Thompson, and

Morrison microphysics schemes, and the Grell-Devenyi cumulus scheme perform better in the rest of California. However, all microphysics schemes substantially overestimate precipitation for the La Nina type of storms in all regions except the coast. The impact of planetary boundary layer, soil-layer, and radiation physics on precipitation is weaker than their counterparts in microphysics and cumulus processes for short- to medium-range low-resolution simulations. The use of PBL, soil layer, and radiation transfer options other than the control setting causes a weak increase in precipitation forecast bias.

High-resolution (2-km) grids act to enhance model precipitation in all regions. As a result, it greatly improves the forecast bias in the coastal region while it downgrades the model performance in the other regions. This result suggests that the smaller length scale of coastal ranges needs higher horizontal grid resolution to better resolve the orographic forcing. In addition, horizontally uniform microphysics properties may be another cause of the degraded model performance in the inland regions. For example, the cloud condensation nuclei (CCN) number in the Thompson scheme is set by default to 100 per cm^{-3}. CCN concentrations over land are likely much larger values, which would slow down the auto-conversion of rainwater (Resenfeld et al., 2001). The default setting of graupel density in the Thompson scheme is specified at 0.4 g cm^{-3}, but observations show it to range between 0.1 – 0.85 g cm^{-3} (Pruppacher and Klett, 1997). Lower graupel density can lead to smaller fall velocity (Khain et al., 2001), which could reduce the growth of precipitation. Therefore, more sophisticated microphysics treatment may be needed to improve precipitation bias in the inland regions of high-resolution simulations.

In addition, both Kain-Fritsch and Grell-Devenyi cumulus schemes in low-resolution simulations lead to substantial underestimation of total precipitation for some of selected storms in the coastal region. Since most coastal precipitation appears to be unresolved (convective) at 12-km resolution, this underprediction suggests need for improvement of cumulus schemes. This grid-resolution comparison also supports the use of microphysics schemes in all regions except the coastal region in coarser-grid applications. For regional climate applications, the improvement of convective precipitation in low-resolution simulations seems more practical than the effort on improving stratiform (resolved) precipitation in high-resolution runs due to the large difference in the computational cost.

In conclusion, we have explored a subset of the available WRF parameterizations and found an optimal configuration for simulating precipitation from wintertime storms over California. Our results indicate that model precipitation depends most strongly on microphysics scheme, though convective parameterization is also important, particularly near the coast. Other physics choices are less important for California wintertime precipitation. Even with our "optimal" configuration, WRF tends to underpredict precipitation near the coast and overpredict elsewhere in California. Reducing these biases is critical to improving regional climate prediction, and our study is a first step towards this goal. The fact that none of our parameterization combinations fixed this problem suggests that improvements to the parameterizations themselves are required for accurate climate predictions over California using WRF.

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Figure Captions

Fig. 1. Terrain heights of model domains in units of meters. (a) 12-km resolution, and (b) 2-km resolution. California is divided into four regions; Coast, Central Valley (C_Valley), Mountains (Mtn), and Southern California (S_Cal).

Fig. 2. Daily averages of surface stratiform (upper panels) and convective (lower panels) precipitation of the SC1 case in units of mm/day for five microphysics schemes; Lin, WSM5, Goddard, Thompson, and Morrison.

Fig. 3. Area- and daily-averaged surface (stratiform and convective) precipitation in units of mm/day for all simulated storms (horizontal axis); Pineapple Express (PE), El Nino (EN), La Nina (LN), and synoptic cyclone (SC). Simulations of 12-km resolution with 5 different microphysics schemes (in blue) and the control configuration for the other model physics are compared with three sets of observations (in grey).

Fig. 4. As in Fig.3, except for comparisons with different microphysics and cumulus schemes. Solid bars are for the Kain-Fritsch (KF) cumulus scheme, and open bars for the Grell-Devenyi (GD) scheme.

Fig. 5. As in Fig.3, except for comparisons with different PBL (ACM2), soil-layer.(RUC), and radiation transfer (RRTM LW / Dudhia SW). The physics configuration of control runs contains Morrison microphysics, Grell-Devenyi cumulus scheme, YSU PBL, Noah soil layer, and CAM LW / SW radiation transfer.

Fig. 6. As in Fig. 2, except for total (convective and stratiform) precipitation of high- (upper panels) and low-resolution (lower panels) simulations of four selected storms.

Fig. 7. As in Fig. 3, except for comparisons of both high- and low-resolution simulations with three sets of observations.

Table 1. List of storm events.

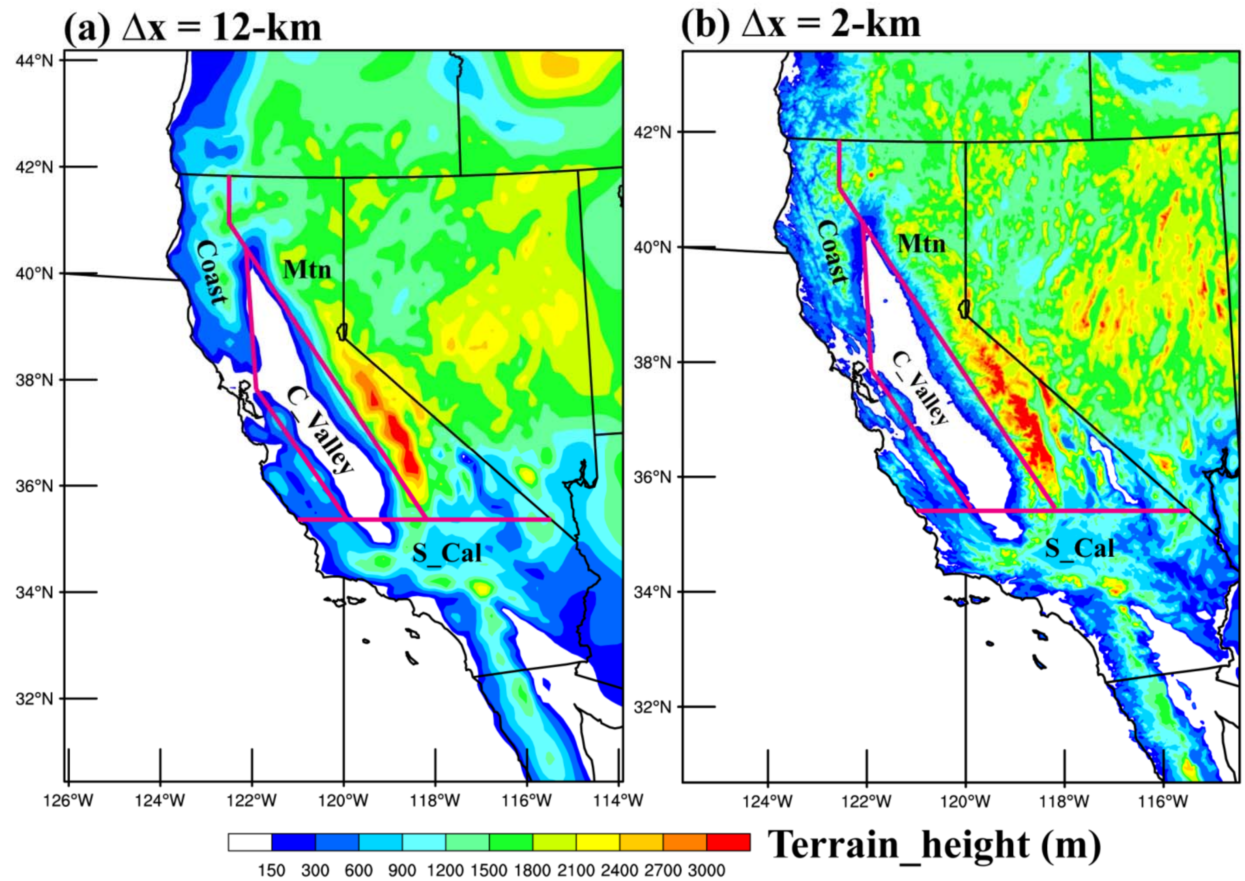
Storm Type	Occurrence Period	Remarks
Pineapple Express	February 10-20, 1986	PE1
Pineapple Express	December 30, 1996-January 4, 1997	PE2
El Nino	March 7-11, 1995	EN1
El Nino	February 18-24, 1998	EN2
La Nina	March 6-10, 1989	LN1
La Nina	March 3-7, 2001	LN2
Synoptic Cyclone	December 10-12, 1995	SC1
Synoptic Cyclone	February 19-22, 1996	SC2

Table 2. List of model physics used.

Physics	Origin
Microphysics	Lin et al (one-moment)
Microphysics	WSM-5 class (one-moment)
Microphysics	Goddard (one-moment)
Microphysics	Thompson (one-moment)
Microphysics	Morrison (two-moment)
Cumulus	Kain-Fritsch
Cumulus	Grell-Devenyi
Soil Layer	Noah
Soil Layer	RUC
PBL	YSU
PBL	ACM2
Radiation	RRTM LW / Dudhia SW
Radiation	CAM LW & SW

Table 3. Area-averaged mean absolute errors of surface precipitation (with respect to UW1 observations, in percentage). These errors are computed from 12-km resolution runs with different microphysics schemes for all storms except for LN2.

Region \ Microphysics	Lin	WSM5	Goddard	Thmopson	Morrison
Coast	11.3	15.1	19.6	17.0	19.5
Mountain	21.3	23.3	16.7	14.7	13.1
Central Valley	76.2	54.2	44.8	44.3	49.9
Sothern California	24.0	26.0	21.6	19.7	22.4



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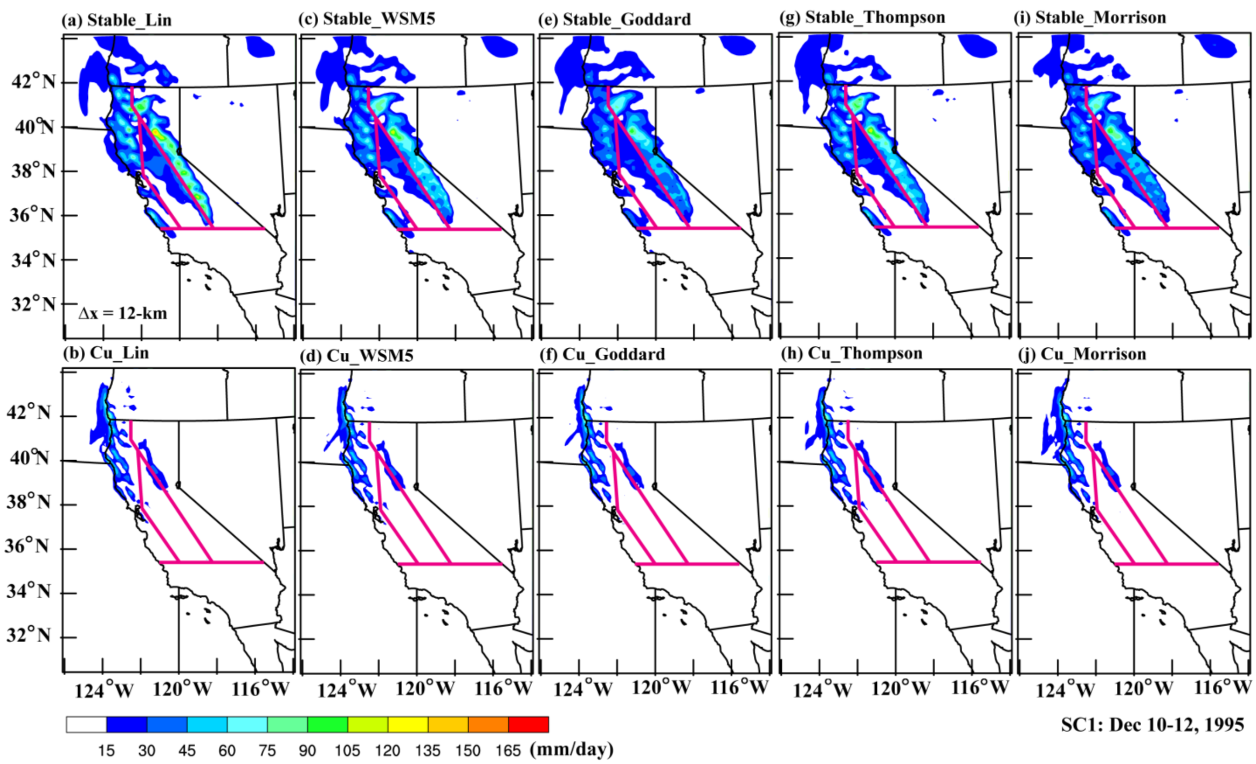

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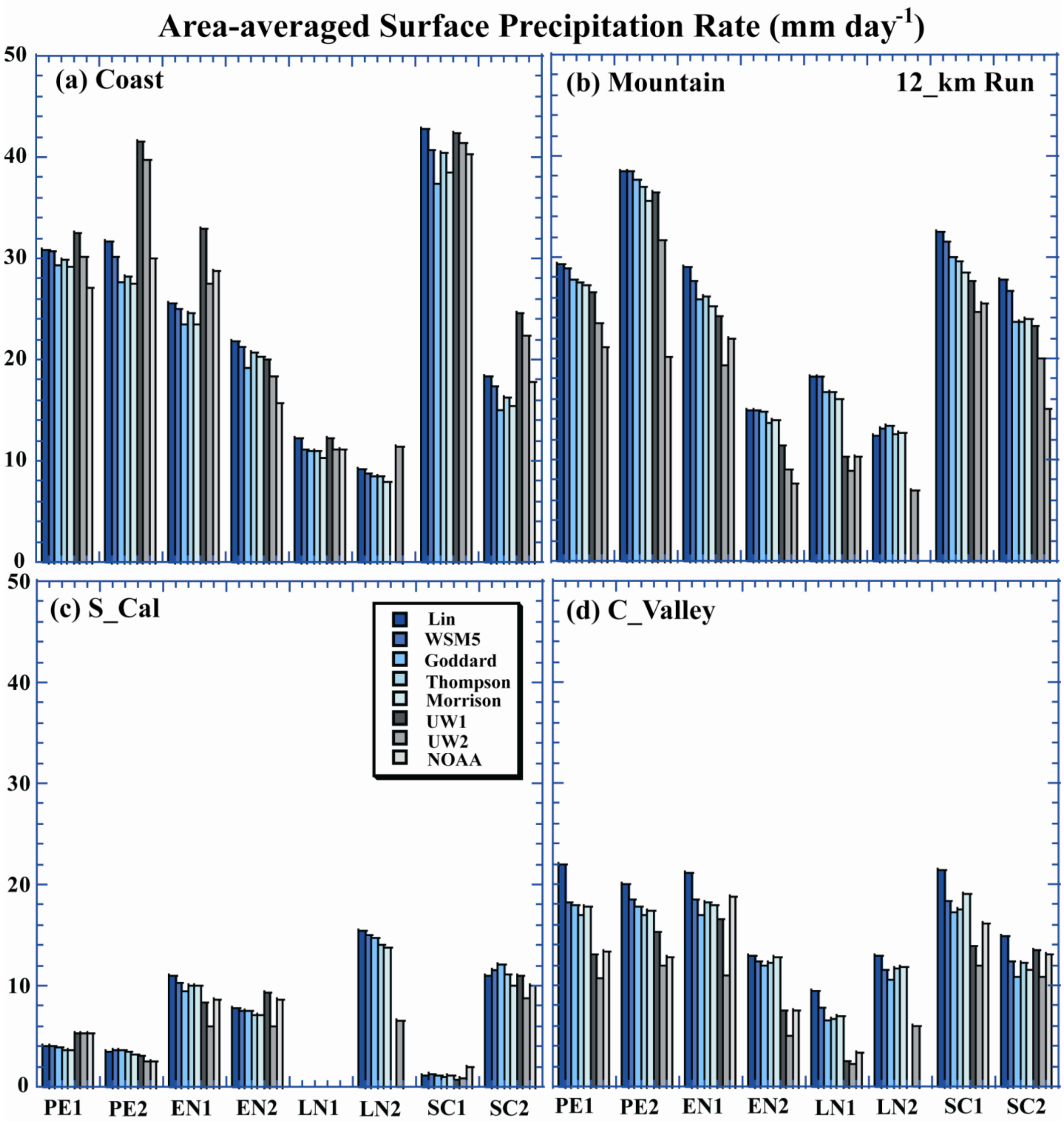
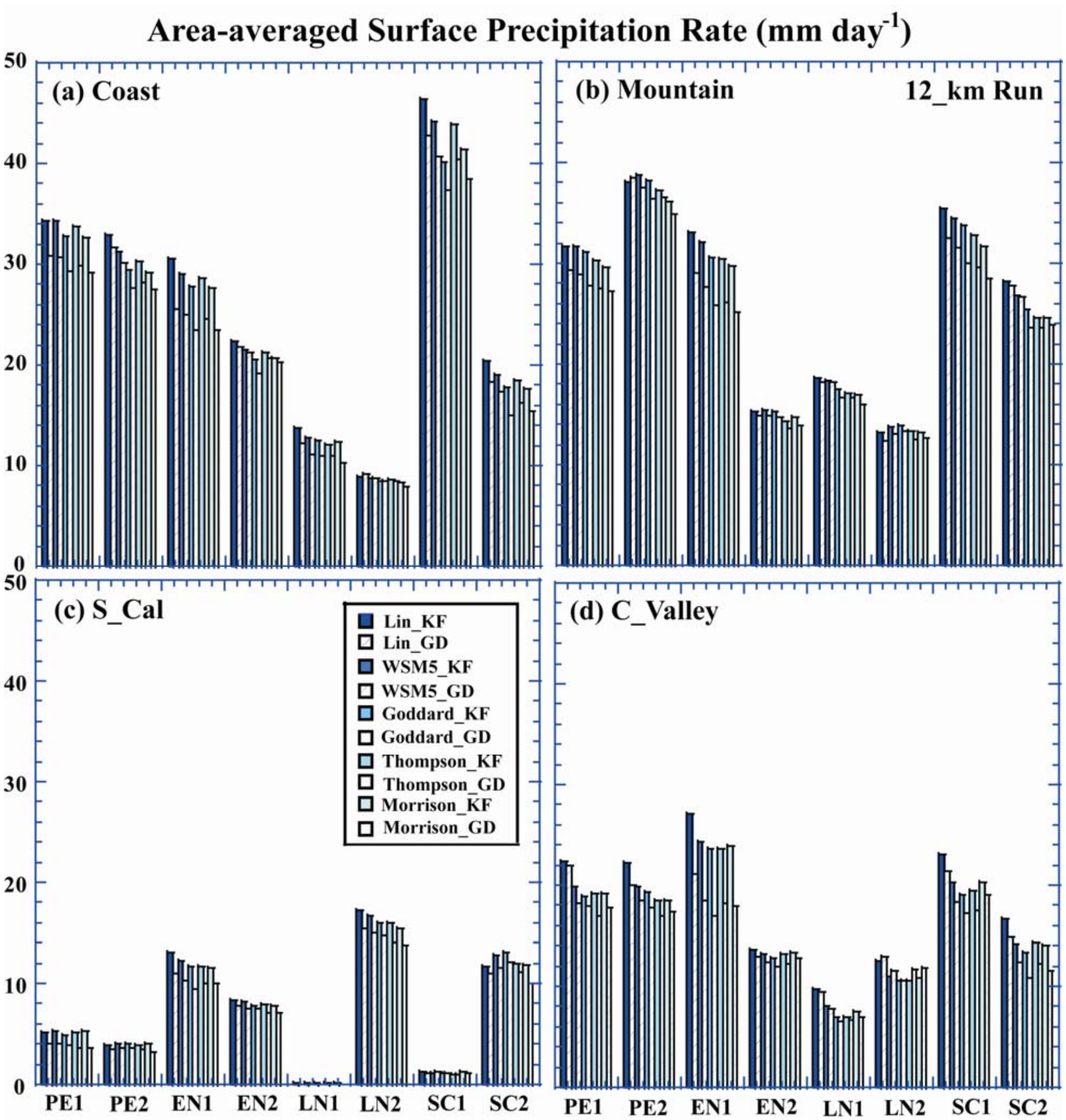


Fig. 3. Area- and daily-averaged surface total (stratiform and convective) precipitation in units of mm/day for all simulated storms (horizontal axis); Pineapple Express (PE), El Nino (EN), La Nina (LN), and synoptic cyclone (SC). Simulations of 12-km resolution with 5 different microphysics schemes (in blue) and the control configuration for the other model physics are compared with three sets of observations (in grey).



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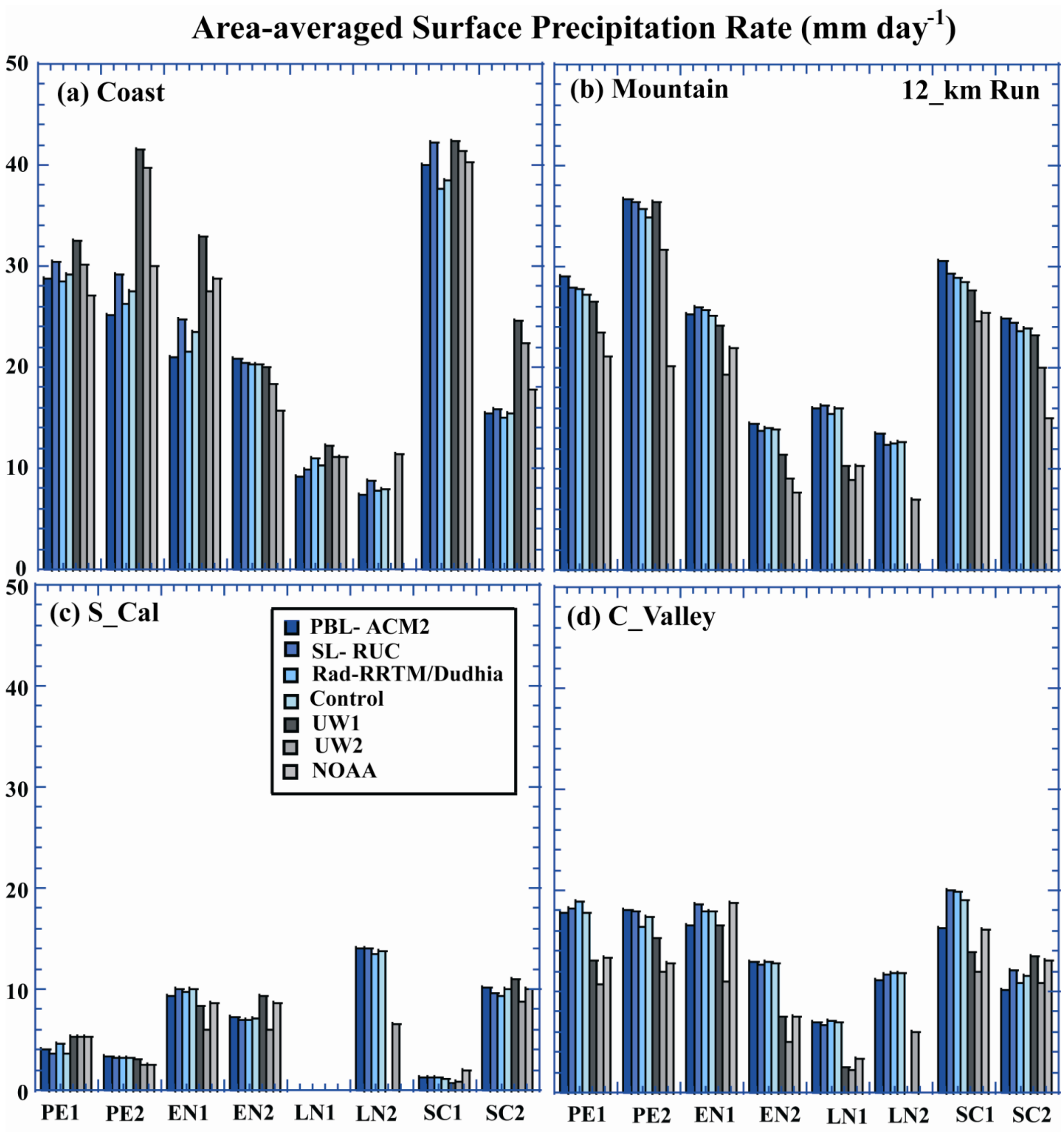

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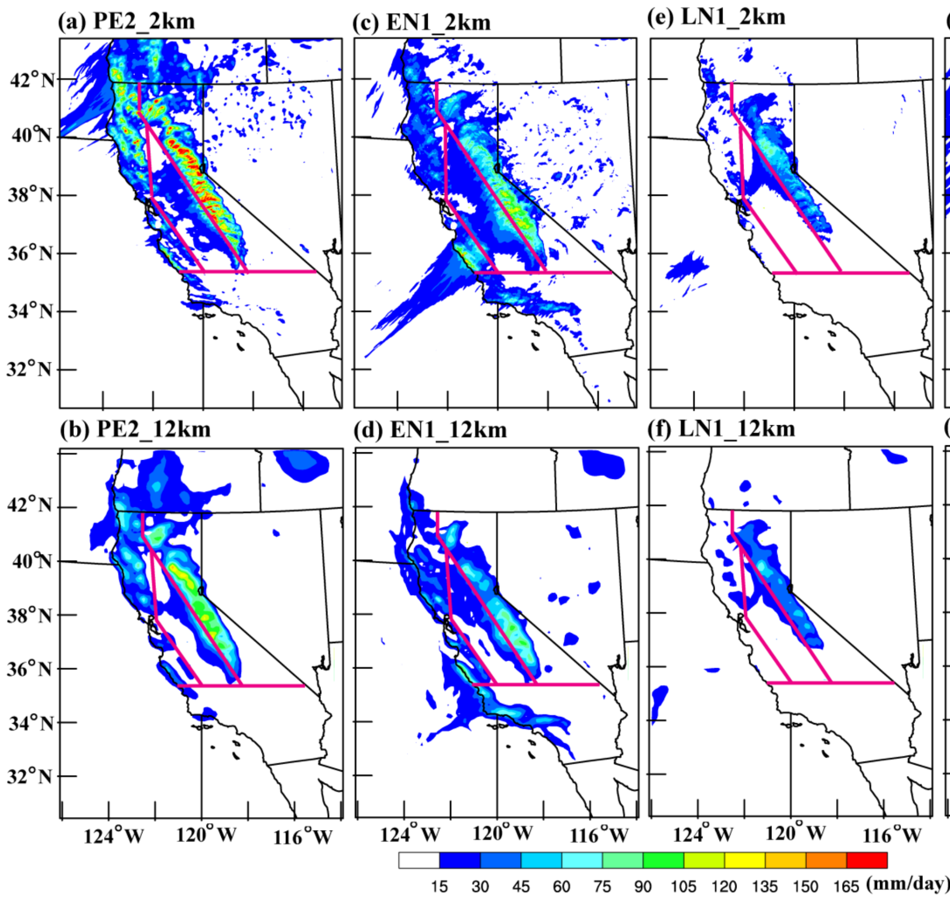

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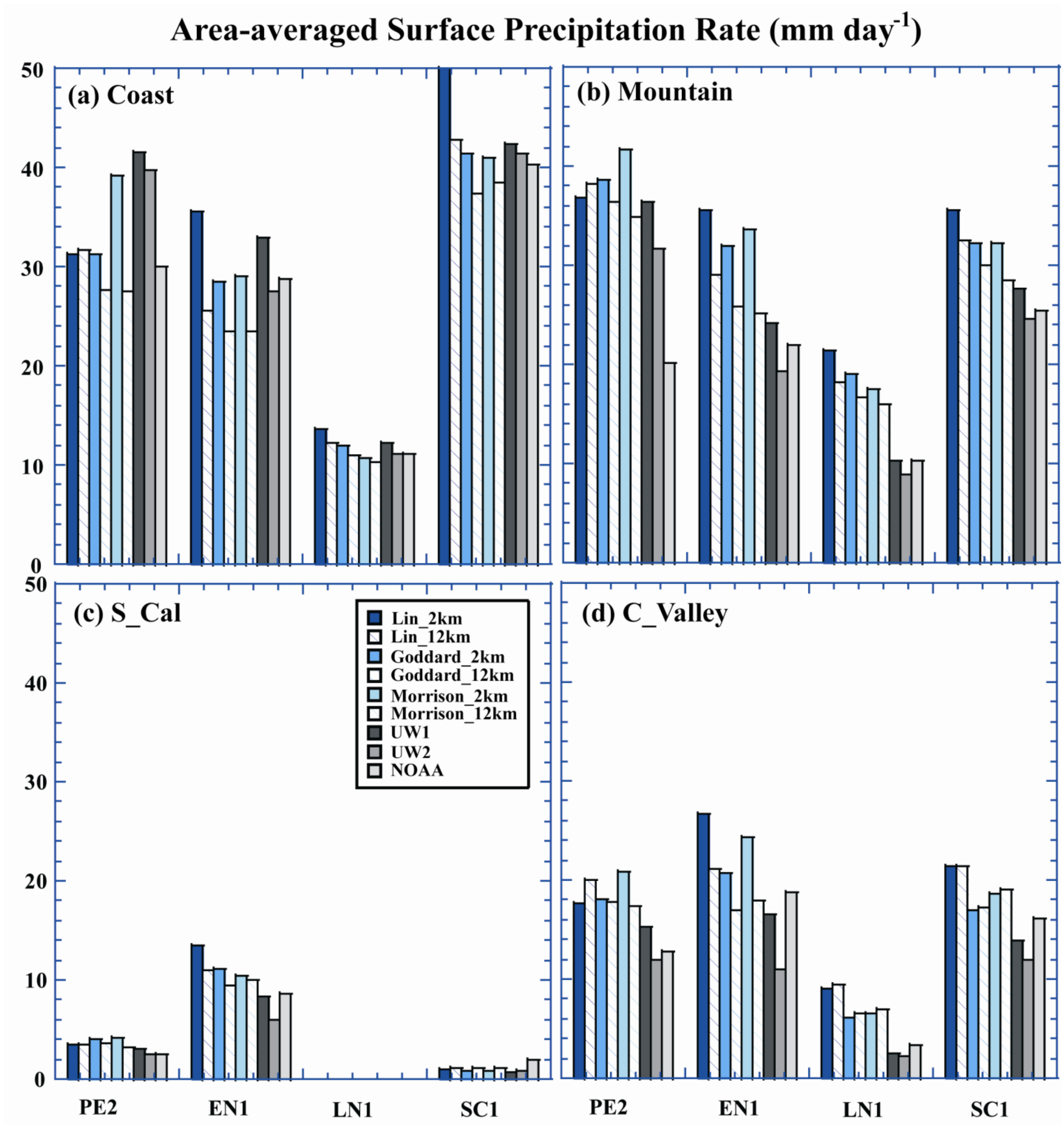

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